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Observation of the B_c Meson at CDF

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OBSERVATION OF THE B_c MESON AT CDF

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We report on the observation of bottom-charm mesons via the decay mode $B_c^\pm \rightarrow J/\psi l^\pm \nu$ in 1.8 TeV $p\bar{p}$ collisions using the CDF detector at the Fermilab Tevatron. A fit of background and signal contributions to the $J/\psi l$ mass distribution yielded $20.4^{+6.2}_{-5.5}$ events from B_c mesons. We measured the B_c^+ mass to be $6.40 \pm 0.39(\text{stat.}) \pm 0.13(\text{syst.})$ GeV/ c^2 and the B_c^+ lifetime to be $0.46^{+0.18}_{-0.16}(\text{stat.}) \pm 0.03(\text{syst.})$ ps. The measured production cross section times branching ratio for $B_c^+ \rightarrow J/\psi l^+ \nu$ relative to that for $B^+ \rightarrow J/\psi K^+$ is $0.132^{+0.041}_{-0.037}(\text{stat.}) \pm 0.031(\text{syst.})^{+0.032}_{-0.020}(\text{lifetime})$.

1 Introduction

The B_c^+ meson is the lowest-mass bound state of quarkonium states containing a charm quark and a bottom anti-quark¹. Since this pseudoscalar ground state has non-zero flavor, it has no strong or electromagnetic decay channels. It is the last such meson predicted by the Standard Model and the only meson with two different heavy quarks. It decays weakly yielding a large branching fraction to final states containing a J/ψ ^{2,3,4,5}. Non-relativistic potential models predict a B_c mass in the range 6.2–6.3 GeV/ c^2 ^{6,7}. In these models, the c and \bar{b} are tightly bound in a very compact system and have a rich spectroscopy of excited states.

The production of B_c mesons has been calculated in perturbative QCD. At transverse momenta p_T large compared to the B_c mass the dominant process is that in which a \bar{b} is produced by gluon fusion in the hard collision and fragmentation provides the c . At lower p_T a full α_s^4 calculation⁸ shows that the dominant process is one in which both the \bar{b} and c quarks are produced in the hard scattering. These and other calculations^{8,9,10,11,12} provide inclusive production cross sections along with distributions in p_T and other kinematic variables.

We expect three major contributions to the B_c decay width: $\bar{b} \rightarrow \bar{c}W^+$ with the c as a spectator, leading to final states like $J/\psi \pi$ or $J/\psi \ell \nu$; $c \rightarrow sW^+$, with the \bar{b} as spectator, leading to final states like $B_s \pi$ or $B_s \ell \nu$; and $\bar{c}\bar{b} \rightarrow W^+$ annihilation, leading to final states like DK , $\tau \nu_\tau$ or multiple pions. Since these processes lead to different final states, their amplitudes do not interfere. When phase space and other effects are included, the predicted lifetime is in the range 0.4–1.4 ps^{2,13,14,15,16,17}. Because of the wide range of predictions, a B_c lifetime measurement is a test of the different assumptions made in the various calculations. Several authors have also calculated the B_c partial widths to semileptonic final states^{2,3,4,5,18}.

Limits on the B_c production have been placed by

various experimental searches at LEP^{19,20,21}. A prior CDF search placed a limit on B_c production in the $B_c^+ \rightarrow J/\psi \pi^+$ decay mode²².

We report here on the first observation of B_c mesons produced in 1.8 TeV $p\bar{p}$ collisions at the Fermilab Tevatron collider using a 110 pb⁻¹ data sample collected with the CDF detector. A more detailed description of this work can be found in Ref.²³. We searched for the decay channels $B_c^+ \rightarrow J/\psi \mu^+ \nu$ and $B_c^+ \rightarrow J/\psi e^+ \nu$ followed by $J/\psi \rightarrow \mu^+ \mu^-$. A Monte Carlo calculation of B_c production and decay to $J/\psi \ell \nu$ showed that, for an assumed B_c mass of 6.27 GeV/ c^2 , 93% of the $J/\psi \ell$ final state particles would have $J/\psi \ell$ masses with $4.0 < M(J/\psi \ell) < 6.0$ GeV/ c^2 . We refer to this as the signal region, but we accepted candidates with $M(J/\psi \ell)$ between 3.35 and 11 GeV/ c^2 .

We have described the CDF detector in detail elsewhere^{24,25}. The tracking system for CDF gives a transverse momentum resolution $\delta p_T/p_T = [(0.0009 \times p_T)^2 + (0.0066)^2]^{1/2}$, where p_T is in units of GeV/ c . The average track impact parameter resolution relative to the beam axis is $(13 + (40/p_T))$ μm in the plane transverse to the beam²⁶. An online di-muon trigger and subsequent offline selection yielded a sample of about 196,000 $J/\psi \rightarrow \mu^+ \mu^-$ mesons.

2 Event Selection

We searched for the B_c through $B_c^+ \rightarrow J/\psi \ell^+ \nu$ decays. These decays have a very simple topology: a decay point for $J/\psi \rightarrow \mu^+ \mu^-$ displaced from the primary interaction point and a third track emerging from the same decay point. This J/ψ + track sample included $B_c^+ \rightarrow J/\psi e^+ \nu$, $B_c^+ \rightarrow J/\psi \mu^+ \nu$, $B^+ \rightarrow J/\psi K^+$, and background from various sources. We subjected the three tracks to a fit that constrained the two muons to the J/ψ mass and that constrained all three tracks to originate from a common point. A measure of the time between production and decay of a B_c candidate is the quantity

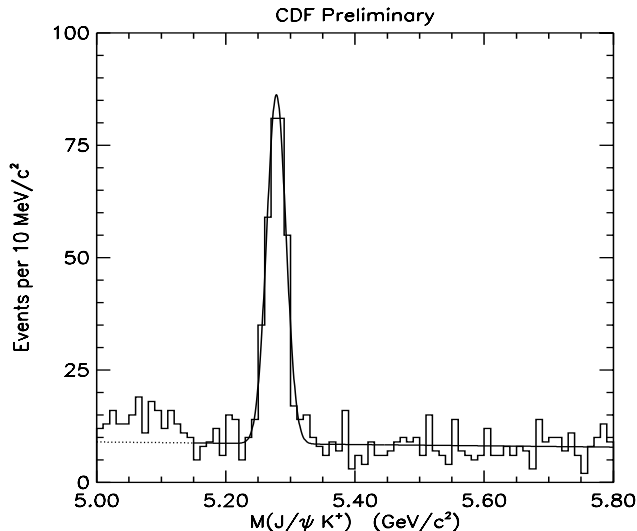


Figure 1: The distribution of masses of $J/\psi K^\pm$ candidates. The solid curve represents a least squares fit to the data between 5.15 and 5.8 GeV/c^2 consisting of a Gaussian signal above a linear background. The area of the Gaussian contribution is 290 ± 19 events.

ct^* , defined as

$$ct^* = \frac{M(J/\psi \ell) \cdot L_{xy}(J/\psi \ell)}{|p_T(J/\psi \ell)|} \quad (1)$$

where L_{xy} is the distance between the beam centroid and the decay point of the B_c candidate in the plane perpendicular to the beam direction and projected along the direction of the $J/\psi \ell$ combination in that plane, $M(J/\psi \ell)$ is the mass of the tri-lepton system, and $p_T(J/\psi \ell)$ is its momentum transverse to the beam. Our average uncertainty in the measurement of ct^* is $25 \mu\text{m}$. We required $ct^* > 60 \mu\text{m}$.

$B^+ \rightarrow J/\psi K^+$ candidates were identified by a peak in the $\mu^+ \mu^- K^+$ mass distribution centered at $M(B^+) = 5.279 \text{ GeV}/c^2$ with an r.m.s. width of $14 \text{ MeV}/c^2$. (See Fig. 1.) The peak contained 290 ± 19 events after correction for background. Events within $50 \text{ MeV}/c^2$ of $M(B^+)$ were eliminated as $B_c^+ \rightarrow J/\psi \ell^+ \nu$ candidates.

Electrons were identified by the association of a charged-particle track with $p_T > 2 \text{ GeV}/c$ and an electromagnetic shower in the calorimeter. Additional information for identifying electrons was obtained from specific ionization in the tracking chambers and from the shower profile in proportional chambers embedded in the electromagnetic calorimeter. Muons from J/ψ decay were identified by matching a charged-particle track with $p_T > 2 \text{ GeV}/c$ to a track segment in muon drift chambers outside the central calorimeter (5 to 9 interaction lengths

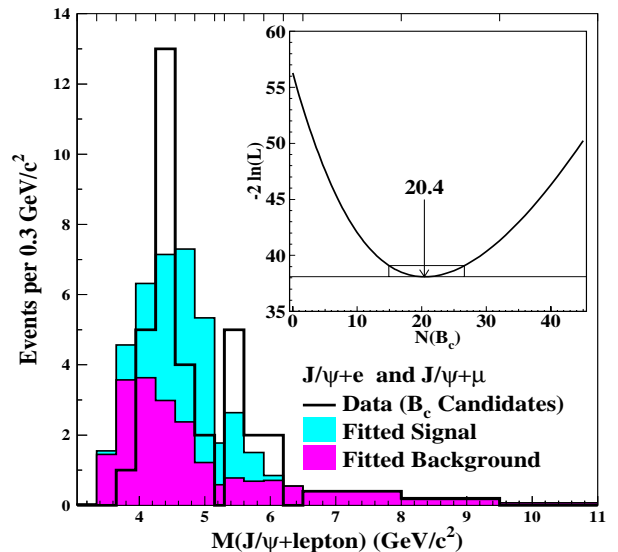


Figure 2: Histogram of the $J/\psi \ell$ mass that compares the signal and background contributions determined in the likelihood fit to the combined data for $J/\psi e$ and $J/\psi \mu$. Note that the mass bins, indicated by tick marks at the top, vary in width. The total B_c contribution is $20.4^{+6.2}_{-5.5}$ events. The inset shows the behavior of the log-likelihood function $-2 \ln(L)$ vs. the number of B_c mesons.

thick depending on angle). The third muon was required to have a transverse momentum exceeding $3 \text{ GeV}/c$ and to pass through an additional three interaction lengths of steel to produce a track segment in a second set of drift chambers. We found $23 B_c^+ \rightarrow J/\psi e^+ \nu$ candidates of which 19 were in the signal region, and we found $14 B_c^+ \rightarrow J/\psi \mu^+ \nu$ candidates of which 12 were in the signal region.

3 Background Determination

The major contributions to backgrounds in the sample of B_c candidates come from misidentification of hadron tracks as leptons (*i.e.* false leptons) and from random combinations of real leptons with J/ψ mesons. There are three significant sources of false leptons: hadrons that reach the muon detectors without being absorbed; hadrons that decay in flight into a muon in advance of entering the muon detectors; and hadrons that are falsely identified as electrons. In one type of random combination, electrons from photons that convert to $e^+ e^-$ pairs in the material around the beam line or from Dalitz decay of π^0 contribute to a “conversion background” when the other member of the pair remains undetected. The other type of random combination involves a B that has decayed into a J/ψ and an associated \bar{B} that has de-

cayed semileptonically (or through semileptonic decays of its daughter hadrons) into a muon or an electron. The displaced J/ψ and the lepton can accidentally appear to originate from a common point. A number of other backgrounds²³ were found to be negligible. From a combination of data and Monte Carlo calculations, we determined the J/ψ + track mass distribution for each of the sources of background. As a check of our background calculations, we verified that we are able to predict the number of events and mass distribution in an independent, background-rich sample of same-charge, low-mass lepton pairs. (See Fig. 27 in Ref.²³.)

The topology for candidate events was verified by applying all selection criteria except the requirement that the third track intersect the J/ψ vertex. The impact parameter distribution between the third track and the J/ψ vertex has a prominent peak at zero, demonstrating that, for most candidate events, the three tracks arise from a common vertex. (See Fig. 28 in Ref.²³.)

In Table 1 we summarize the results of the background calculation and of a simultaneous fit for the muon and electron channels to the mass spectrum over the region between 3.35 and 11 GeV/ c^2 . Figure 2 shows the mass spectra for the combined $J/\psi e$ and $J/\psi \mu$ candidate samples, the combined backgrounds and the fitted contribution from $B_c^+ \rightarrow J/\psi \ell^+ \nu$ decay. The fitted number of B_c events is $20.4^{+6.2}_{-5.5}$.

4 Test of Significance and Determination of the B_c Lifetime and Mass

To test the significance of this result, we generated a number of Monte Carlo trials with the statistical properties of the backgrounds, but with no contribution from B_c mesons. These were subjected to the same fitting procedure to determine contributions consistent with the signal distribution arising from background fluctuations. The probability of obtaining a yield of 20.4 events or more is 0.63×10^{-6} , equivalent to a 4.8 standard-deviation effect.

To check the stability of the B_c signal, we varied the value assumed for the B_c mass. We generated signal templates, *i.e.* Monte Carlo samples of $B_c^+ \rightarrow J/\psi \ell^+ \nu$, with various values of $M(B_c)$ from 5.52 to 7.52 GeV/ c^2 . The signal template for each value of $M(B_c)$ and the background mass distributions were used to fit the mass spectrum for the data. This study established that the magnitude of the B_c signal is stable over the range of theoretical predictions for $M(B_c)$, and the dependence of the log-likelihood function on mass yielded $M(B_c) = 6.40 \pm 0.39$ (stat.) ± 0.13 (syst.) GeV/ c^2 .

We obtained the mean proper decay length $c\tau$ and hence the lifetime τ of the B_c meson from the distribution of ct^* . We used only events with $4.0 < M(J/\psi \ell) < 6.0$

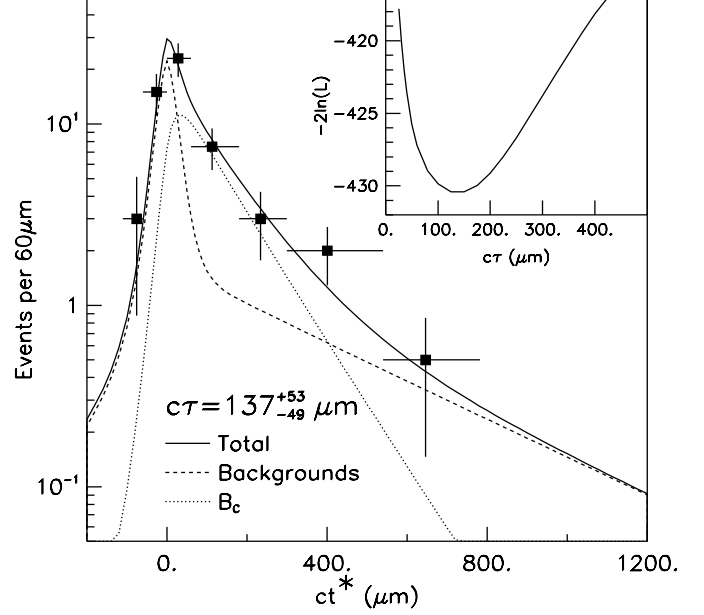


Figure 3: The distribution in ct^* for the combined $J/\psi \mu$ and $J/\psi e$ data along with the fitted curve and contributions to it from signal and background. The inset shows the log-likelihood function vs. $c\tau$ for the B_c .

GeV/ c^2 , and we changed the threshold requirement on ct^* from $ct^* > 60 \mu m$ to $ct^* > -100 \mu m$ for this lifetime measurement. This yielded a sample of 71 events, 42 $J/\psi e$ and 29 $J/\psi \mu$. We determined a functional form for the shapes in ct^* for each of the backgrounds. To these, we added a resolution-smeared exponential decay distribution for a B_c contribution, parameterized by its mean decay length $c\tau$. Because of the missing neutrino, the proper decay length ct for each event differs from ct^* of Eq. 1. We convoluted the exponential in ct with the distribution of ct^*/ct derived from Monte Carlo studies. Finally, we incorporated the data from each of the candidate events in an unbinned likelihood fit to determine the best-fit value of $c\tau$. The data and the signal and background distributions are shown in Fig. 3, and the result is:

$$c\tau = 137^{+53}_{-49} \text{ (stat.)} \pm 9 \text{ (syst.) } \mu m \quad (2)$$

$$\tau = 0.46^{+0.18}_{-0.16} \text{ (stat.)} \pm 0.03 \text{ (syst.) } \text{ps} \quad (3)$$

From the 20.4 B_c events and the 290 $B^+ \rightarrow J/\psi K^+$ events, we calculated the B_c production cross section times the $B_c^+ \rightarrow J/\psi \ell^+ \nu$ branching fraction $\sigma \cdot BR(B_c^+ \rightarrow J/\psi \ell^+ \nu)$ relative to that for the topologically similar decay $B^+ \rightarrow J/\psi K^+$. Systematic uncertainties arising from the luminosity, from the J/ψ trigger efficiency, and from the track-finding efficiencies cancel in the ratio. Our Monte Carlo calculations yielded the

Table 1: B_c Signal and Background Summary

| | $3.35 < M(J/\psi \ell) < 11.0 \text{ GeV}/c^2$ | |
|---|--|---------------------|
| | $J/\psi e$ Events | $J/\psi \mu$ Events |
| False Electrons | 4.2 ± 0.4 | |
| Undetected Conversions | 2.1 ± 1.7 | |
| False Muons | | 11.4 ± 2.4 |
| $B\bar{B}$ bkg. | 2.3 ± 0.9 | 1.44 ± 0.25 |
| Total Background (predicted) | 8.6 ± 2.0 | 12.8 ± 2.4 |
| (from fit) | 9.2 ± 2.0 | 10.6 ± 2.3 |
| Predicted $N(B_c \rightarrow J/\psi e \nu)/N(B_c \rightarrow J/\psi \ell \nu)$ | 0.58 ± 0.04 | |
| e and μ Signal (derived from fit) | $12.0^{+3.8}_{-3.2}$ | $8.4^{+2.7}_{-2.4}$ |
| Total Signal (fitted parameter) | $20.4^{+6.2}_{-5.5}$ | |
| Signal + Background | 21.2 ± 4.3 | 19.0 ± 3.5 |
| Candidates | 23 | 14 |
| Probability for background alone to fluctuate to the apparent signal of 20.4 events | 0.63×10^{-6} | |

values for the efficiencies that do not cancel. The detection efficiency for $B_c^+ \rightarrow J/\psi \ell^+ \nu$ depends on $c\tau$ because of the requirement that $ct^* > 60 \mu\text{m}$, and we quote a separate systematic uncertainty because of the lifetime uncertainty. We assumed that the branching fraction is the same for $B_c^+ \rightarrow J/\psi e^+ \nu$ and $B_c^+ \rightarrow J/\psi \mu^+ \nu$. We multiply the 20.4 events by a factor 0.85 ± 0.15 to correct for other B_c decay channels such as $B_c \rightarrow \psi' \ell \nu$ ²³. We find

$$\mathcal{R}(J/\psi \ell \nu) \equiv \frac{\sigma(B_c) \cdot BR(B_c \rightarrow J/\psi \ell \nu)}{\sigma(B) \cdot BR(B \rightarrow J/\psi K)} =$$

$$0.132^{+0.041}_{-0.037} (\text{stat.}) \pm 0.031 (\text{syst.})$$

$$^{+0.032}_{-0.020} (\text{lifetime}), \quad (4)$$

for B_c^+ and B^+ with transverse momenta $p_T > 6.0 \text{ GeV}/c$ and rapidities $|y| < 1.0$. This result is consistent with limits from previous searches^{19,20,21}. Figure 4 compares phenomenological predictions with our measurements of $c\tau$ and $\mathcal{R}(J/\psi \ell \nu)$. Within experimental and theoretical uncertainties, they are consistent.

5 Conclusions

In conclusion, we report the observation of B_c mesons through their semileptonic decay modes, $B_c \rightarrow J/\psi \ell X$ where ℓ is either an electron or a muon. We measured the B_c mass and the product of its production cross section times semileptonic branching fraction, which confirm phenomenological expectations. We measured a B_c lifetime consistent with calculations in which the decay width is dominated by the decay of the charm quark.

The increase of statistics expected in Run II of the Tevatron Collider (increase in yield by at least a factor of 30), combined with refinement in technique and investigation of additional decay channels for the B_c meson should allow us to measure its mass, lifetime and production cross section with much better accuracy than we did with the currently available data. It should also allow us to measure ratios of branching ratios of the B_c for various decay channels.

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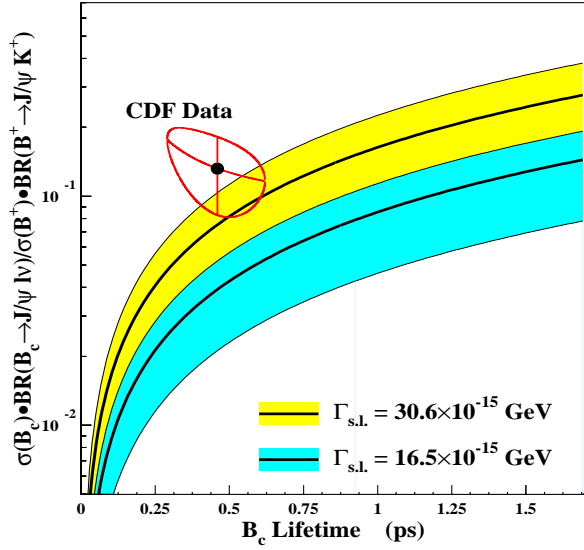


Figure 4: The point with 1-standard-deviation contour shows our measured value of the $\sigma \cdot BR$ ratio plotted at the value we measure for the B_c lifetime. The shaded region represents theoretical predictions and their uncertainty corridors for two different values of the semileptonic width, $\Gamma_{s.l.} = \Gamma(B_c \rightarrow J/\psi \ell \nu)$ based on Refs. 2 and 4. The other numbers assumed in the theoretical predictions are $V_{cb} = 0.041 \pm 0.005$ ²⁷, $\sigma(B_c^+)/\sigma(\bar{b}) = 1.3 \times 10^{-3}$ ⁹, $\frac{\sigma(B^+)}{\sigma(\bar{b})} = 0.378 \pm 0.022$ ²⁷, $BR(B^+ \rightarrow J/\psi K^+) = (1.01 \pm 0.14) \times 10^{-3}$ ²⁷.

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